Micro-optics for high-efficiency optical performance and simplified tracking for concentrated photovoltaics (CPV)*

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Abstract: Micro-optical 5mm lenses in 50mm sub-arrays illuminate arrays of photovoltaic cells with 49X concentration. Fine tracking over ±10° FOV in sub-array allows coarse tracking by meter-sized solar panels. Plastic prototype demonstrated for 400nm<λ<1600nm.

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Introduction: Microsystem Enabled Photovoltaics (MEPV) is a new concept that promises benefits in efficiency, functionality, and cost compared to traditional PV approaches [1,2]. A MEPV module consists of heterogeneously integrated arrays of stacked ~20 μm thick, small (d~0.5 mm) cells with micro-optics concentration, flexible electrical configurations of the individual cells, and potential integration with electronic circuits [3]. With cell lateral dimensions ranging from hundreds of microns to a few millimeters, a module has tens to hundreds of thousands of cells, in contrast to today's PV modules with less than 100. In this paper, we present a micro-optical lens design for this application.

Sub-arrays of about a hundred 5-mm lenses are mounted in meter-sized arrays. (Fig. 1) Figs 2a and 2b show the lens system with the sun in two different positions: on-axis and 10^0 off-axis. As shown in Fig. 3 each lens contains a stack of three aspheric plastic lenses that feeds a 0.7mm diameter photovoltaic (PV) cell stack. The sub-array is thus composed of three plastic plates, each containing ~100 lenses, and an array of ~100 micro-scale PV cell stacks mounted in the rear. The intensity on each PV cell is about 49 suns. The spectral band of the system is 400nm < λ < 1600nm. We could use a standard triple junction PV cell which has three PV layers sandwiched together and wired in series as has been done in the past[4]. The new micro-optical design presented here allows the PV layers to be separated by dielectric layers so they can be wired in parallel rather than series so they can be independently optimized with respect to PV material type, wave band, and current output. Furthermore, there is no need for lattice-matching the PV materials so there are more PV materials to choose from, thus allowing greater efficiency. The PV cells in the stack can be separated by μm's, or mm's if variable magnification is desirable.

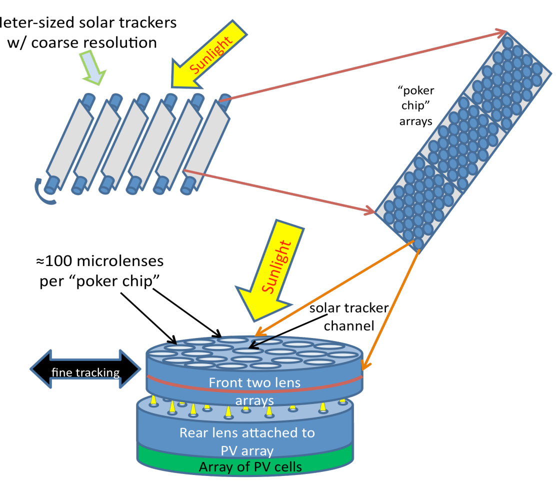
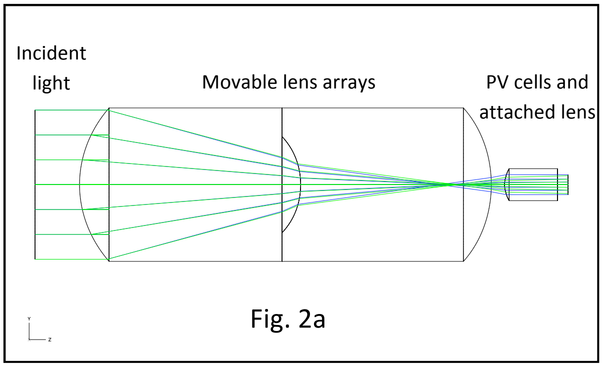


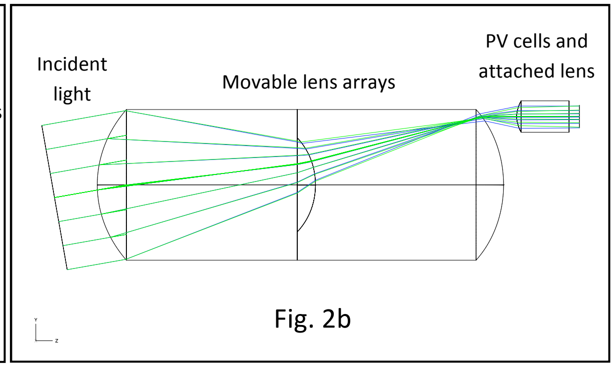
Fig. 1 System overview

Each ≈50mm sub-array has a MEMS-based internal tracking mechanism integrated into the sub-array that operates in two dimensions over a ±10° field of view with an accuracy of a few milliradians (Fig. 3). This allows the meter-sized solar panel (the array of sub-arrays) to track the sun rather coarsely since fine tracking is done in each sub-array. On earth we anticipate a 1-D coarse tracker that realigns every hour; while solar panels on a spacecraft would have to be re-pointed approximately every 10 minutes.

The design of the lens array:

As stated above, there are three arrays of plastic lenses in each sub-array. The first is a "crown-like" plastic (i.e. Zeonex E48R) and the second is "flint-like" (i.e. polycarbonate), which allows for color correction. The third set of lenses is also made from the easily machined Zeonex E48R. The front two lens arrays are attached to one-another, while the third array is fixed to the array of photovoltaic cells. These two units are moved laterally relative to one another to affect tracking (see Fig. 2 and 3 for system diagram).





Figs. 2a & 2b: Lens System with the sun on-axis and 10° off-axis

The alignment system in the 50-mm sub-arrays uses one of the lens pairs in the front array to illuminate a quadrant cell as shown in Fig 3.

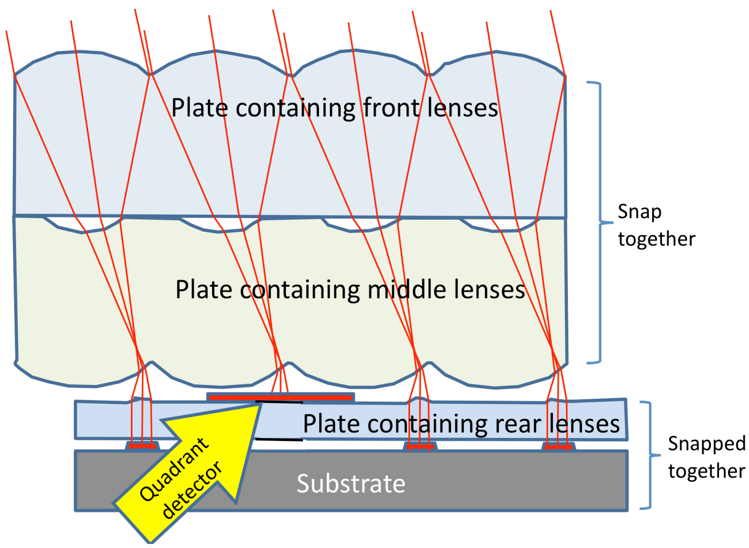


Fig. 3 Lens plates and quadrant

As mentioned above, the data from the quadrant detectors can be used to position individual sub-arrays, compensating for incident light angles of up to ±10°. Additionally, the data from the detectors can be used to align the entire array.

Design of the cell stack:

A typical MEPV cell stack is sketched in Fig. 4. The PV layers in each stack are separated by dielectric layers so they can be wired independently. A wide range of material types is being studied and three- four-, and five-layer PV stacks are under consideration. Because each PV cell is a separate unit, there is no need for lattice matching the materials. This provides increased flexibility in the selection of materials.

Of highest concern in this study is overall efficiency, with ease of fabrication and cost being considered in that order. Fig. 5 shows the absorption of a typical stack for independent readout for four PV materials in the stack. The simultaneous use of several PV materials, each with a different band gap, allows us to take full advantage of the range of wavelengths in visible light, near IR, and short-wave IR.

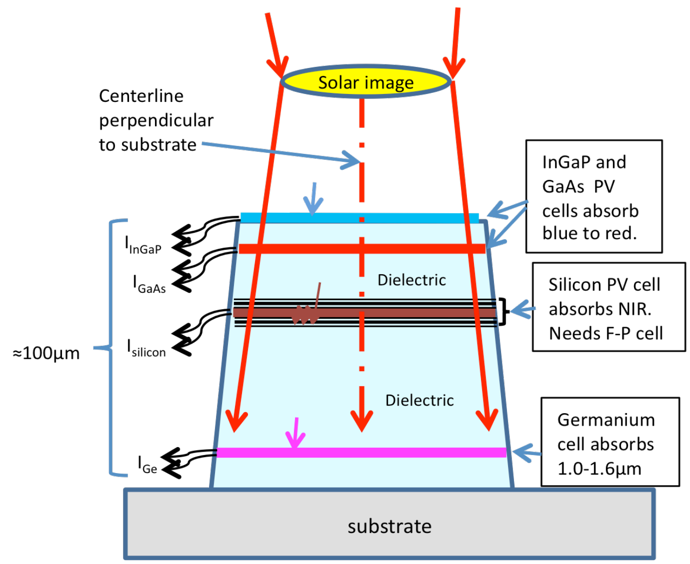


Fig 4: Prototype PV Cell

None of the materials incorporated in the stack have PV efficiencies greater than 20% under normal conditions (i.e. no magnification). When combined in a stack with parallel readouts, the materials complement each other, allowing the overall stack theoretical efficiency to approach 50%. Fig. 5 provides a visual demonstration of the effects of stacking. Each of the colored lines corresponds to a different PV material, with each one reaching its peak power absorption at a particular wavelength. The magenta line demonstrates how stacking effectively compensates for the steep drop off in each material's efficiency by allowing the next material to pick up the slack. Thus, the whole of the target wavelength range of 400nm < λ < 1600nm is used.

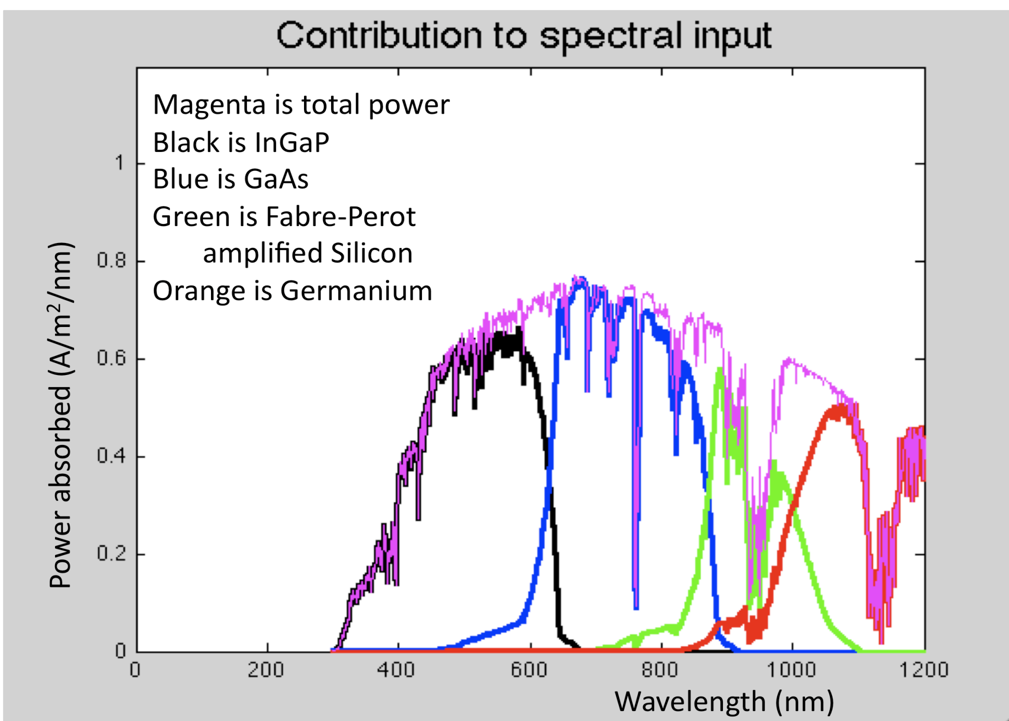


Fig. 5 Power absorption of individual materials and a stacked system

Design Drivers

Several new features have been implemented in this system that increase energy efficiency and minimize the use of materials. The result is a system that maximizes power generated per unit area and power generated per unit mass, so this research is of great interest to the satellite community. The cost in dollars per watt is also fairly reasonable, making this system interesting for military applications and for the tops of buildings.

We next present the system drivers that lead us to design a magnifying microsystem. We also discuss the drive for parallel readouts, and collimation and telecentricity in the PV space. The system features are listed in the table below, each under the overarching design driver that it most closely addresses, though there is significant overlap between the two. For example, using micro-lens arrays for concentration contributes significantly to both energy efficiency and material efficiency.

Table 1 Design Drivers and Contributing Features

Energy Efficiency	Material Efficiency
Magnification Collimated Light Output Independent PV Cell Wiring	Micro-Optics Magnification Integrated Tracking

These features are discussed in detail in corresponding sections below. Finally, an in-depth description of the micro-optics design is presented.

FACTORS AFFECTING ENERGY EFFICIENCY.

What is the advantage of magnification?

Magnification increases the efficiency of most PV cells. Silicon is a good example. Fig 6 shows the theoretical efficiency of a sun-illuminated silicon cell with a range of illumination levels from one to 1000 suns. Note that increasing the magnification from one up to 49X increases the maximum efficiency of silicon from 31% to 35%, an increase of 1.14X. This is entirely due to the device voltage increasing with more current, in this case from 0.77V to 0.94V. This was calculated with an AM1.5 spectrum.

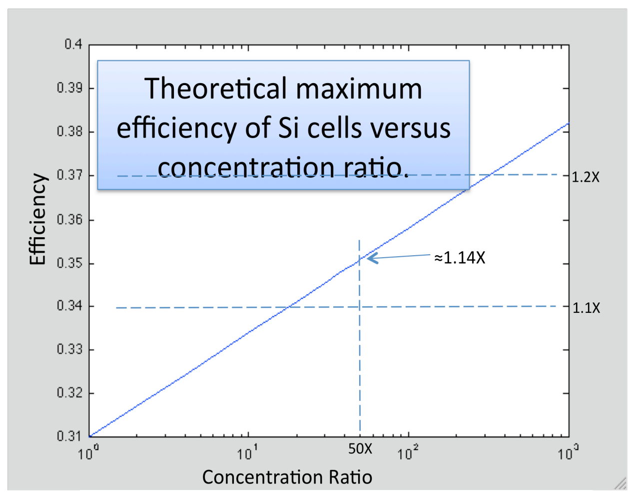
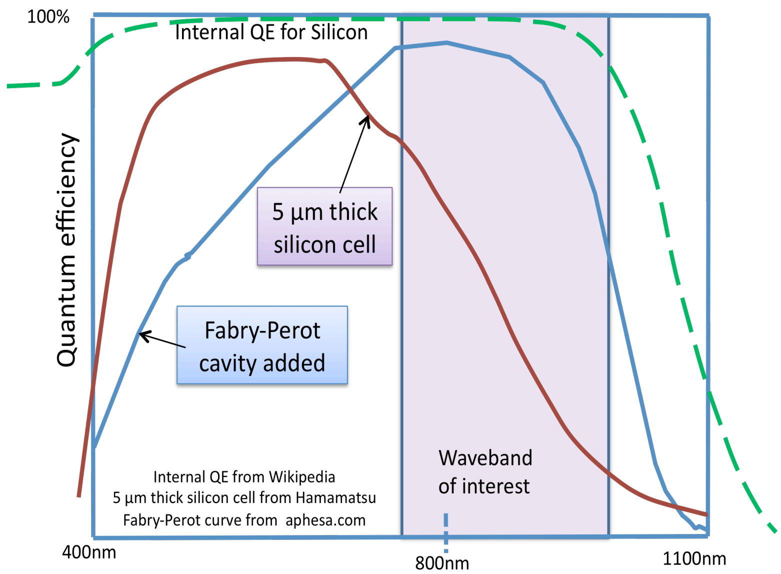


Fig. 6 Effects of magnification on

An area magnification of 49X was chosen for our first design because it increases the efficiency and dramatically reduces the amount of III-V material needed in the PV cells. Higher magnifications are possible for future designs but the mechanical and thermal tolerances and the image quality and alignment accuracy associated with more magnification would all be harder to achieve. An area magnification of 49X seemed like a reasonable compromise for a first prototype.

Why use a collimated, telecentric output beam?

A collimated input beam at the PV cells makes the design of an antireflective coating almost reasonable. All of the PV materials have very high indices of refraction ranging from n≈3 to n=4 so the Fresnel reflections of bare detector surfaces are high (25% to 36%). Applying dielectric coatings is problematic because of the wide wavelength band (400nm ≤ λ ≤ 1600nm) and the high index break. With a collimated input beam (as in this



case), this is a difficult problem. If one adds the complexity of a large range of angles of incidence, the problem is much harder—perhaps intractable.

With a collimated input beam, certain of the PV layers with low absorption per unit length, such as silicon, can be beneficially surrounded by a "low Q" Fabry-Perot (FP) cavity which increases the absorption of the sunlight near the band edge. By "low-Q" we mean $2 < Q < \sim 4$. The cavities should be tuned to increase the intensity near the band edge where the absorption is dropping, and yet if a photon were absorbed, the energy conversion efficiency would be highest. To demonstrate this, in Fig. 7 we plot the theoretical absorption efficiency of a very thick piece of silicon, the absorption of a silicon cell that is only 5-µm thick and finally, that cell's absorption when a FP cavity is wrapped around it. Note that the silicon wafer without the FP cell transmits most of the light near 1000nm. The FP cavity increases the absorption near the band edge, magnifying the absorbed light by (Q=) ≈4X near 1000 nm.

It also should be mentioned that each micro-optical system is fairly well color corrected. The different colored beam bundles are reasonably well overlapped on the front PV cell, and are nearly the same size. This minimizes the sizes of the PV cells. Further, imaging for all colors is essentially telecentric. Thus the PV stack will see essentially the same image anywhere within the $\pm 10^0$ field of view, and again, this allows the sizes of the cells to be minimized.

<u>Why wire the PV layers in independently rather than in series?</u>

The most important reason for wiring the PV cells in parallel is to improve efficiency. In a standard triple junction where the PV materials are connected in series, the PV layers must be latticed-matched and the current is by definition the same in all PV cells. The lattice-matching requirement limits the number of possible PV materials, ruling out some very efficient ones.

The current matching requirement for triple junctions is perhaps more problematic. The wave bands must be adjusted so that under a chosen condition (e. g. at noon on a 5% cloud cover day at the equinox) the current through the three cells can all be made equal by material choices. This means that the materials have to be formulated for maximum efficiency with the appropriate (but not necessarily optimal) wave band included in the calculation.

Wiring the PV cells in independently loosens these requirements. One arrangement is to connect different numbers of each cell type in series to yield a common intermediate voltage and then connect those in parallel [3]. The lattice-matching requirement goes away entirely. The PV materials can be chosen to optimally collect all of the sunlight, and if the currents generated within the different materials are different, so be it. We choose, for example, Germanium and Silicon for the SWIR and NIR spectral ranges, and some combination of InGaP, GaN, GaAs, or other material combinations for the visible range.

Also, as we allude to above, the relative current in the different PV materials changes with time of day, time of year, cloud cover, and air pollution. With a series connected triple junction cell, the maximum current through the stack will be set by the poorest performing cell. For an example, see Fig. 8. The current in the InGaP and

Germanium PV cells drop significantly more than those in the GaAs and the Silicon late in the afternoon. In fact, the output power of the series read-out stack drops 9% at 4:00pm and 16% at 4:40pm. Reading out the PV cells in parallel avoids this loss.

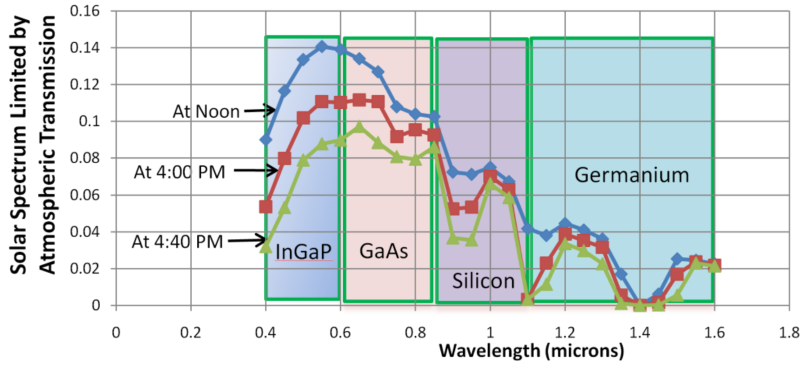


Fig. 8 Atmospheric effects on efficiency

MATERIAL AND WEIGHT MINIMIZATION

Why micro-optics rather than large mirror systems?

An array of micro-optics that has an area of many square meters can be much lighter than an equivalent reflective telescope that images the sun onto a large PV cell. In fact, an array of micro-optics will be almost as light as a flat solar panel. We anticipate a weight of 5-10kg/m^2 for the sub-arrays of microlenses, detectors, and electronics, plus approximately 5kg/m^2 for support structure.

There is a size dependency for the temperature rise of powered systems. If a large system is scaled down to a smaller size, the smaller system will have a lower temperature rise (i.e. in the PV cells) because the thermal conduction paths are shorter. In fact, the temperature reduction seen in a microsystem is roughly proportional to the scale size. Thus the temperature rise of the PV cell will reduce from 100's of degrees for a meter-sized collecting optic to single digit temperature rises in microsystems. Thus micro-photovoltaic systems will not need to be cooled while big systems must in order to maintain efficiency[4].

As was mentioned above, the amount of III-V material needed in the PV system is reduced ≈50X. Thus the most efficient PV materials can be used, even if they are relatively expensive.

And finally, reasonably small and simple micro-optical systems like the one described here can deliver a collimated, telecentric beam to the PV cells allowing better AR coatings and FP cavities to be used. Note that surrounding a PV cell with an FP cavity increases the energy efficiency and/or allows the PV cell to be thinner.

Why integrate a ±10^0 tracking capability into each lens sub-array?

Each sub-array does its own fine alignment so the coarse tracker holding the meter-sized solar panel can be roughly pointed at the sun. This rough pointing can be done open-loop. The sub-array fine alignment also allows the solar panel to be rather flimsily built, so it can be light and relatively inexpensive. Because of the local tracking, the assembly of the solar panels will require no more than minimal care.

The sub-arrays have to be designed so thermal expansion, structural problems, and assembly errors will not throw some or all of the sub-array out of focus or alignment. The 50-mm diameter sub-array with 100 microlenses seem like a good beginning size that shouldn't warp due to solar heating.

Lens design particulars:
The front two lenses are designed such that they introduce no field curvature (focus shift after the middle lens) so the tracking motion can be in the image plane. The front lenses are also well corrected for primary axial and lateral color so the images delivered to the third lens will have essentially no color defects. The lens surfaces are all diamond-turned or molded in diamond-turned molds so designing with aspheric surfaces rather than spherical ones comes at very little cost. With the aspheres we are able to correct the astigmatism and coma in the front lens pair. The system is designed so that the beam centerline following the middle lens is telecentric. Thus, during tracking the beams delivered to the rear lenses are independent of the sun's position, thus allowing each rear lens to deliver a collimated and telecentric bundle of rays to its PV cells. The telecentricity simplifies the AR coatings on the PV cells. It also allows the PV cells to be axially spaced so they can be mounted on different substrates if desired.

The third lens in each lens column can leave some primary axial color (PAC), if desired. In the prototype design the visible light is largely collimated as it approaches the front two PV cells in the stack. Due to the PAC, the IR beam bundle is slightly smaller and slightly divergent at the front of the PV stack. Thus the IR beam will pass through the visible-light PV cells (always in front) without being vignetted. The IR beam will also gradually grow after it passes through the visible PV cell. With some IR PV materials this option can be an advantage since these materials may be somewhat more efficient with somewhat less solar magnification.

The lenses in the front array should be fitted as close to one another as possible in order to maximize the power collected per unit area (W/cm^2) of the array. In our second-generation system we intend to fabricate them in a closely-spaced hexagonal array. This close-packing affects the first-order design of the lens units. Specifically, the front lens diameter is D_1=5mm so the diameter of the middle lens can be no larger than $D_2 \leq$5mm. This size, plus the telecentricity requirement, forces the system design to be as short as possible. It also limits the range of the internal tracking to be roughly ±10° FOV.

Fabricating the prototype: We have diamond-turned[5] three arrays of four lenses for our pre-prototype system. These arrays have been assembled into a 2 X 2 array of microlenses. We plan to use three of the lens sets to illuminate three PV cells stacks, while the fourth will illuminate a quad cell in the alignment system. We expect to have the complete system assembled soon and plan to show data demonstrating the imaging and solar tracking at the conference.

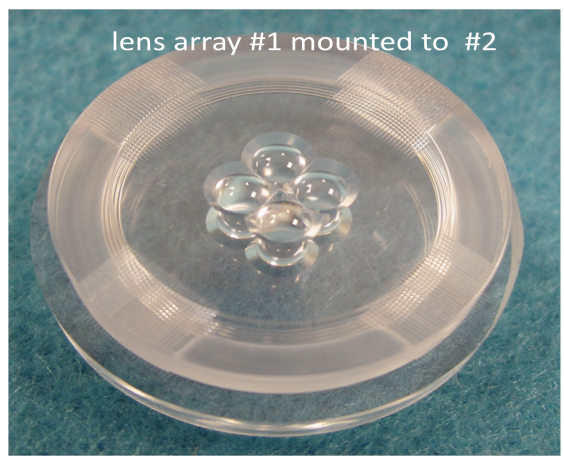


Fig. 9 Prototypes of lens arrays 1 and 2

Design Validation:
The three prototype lenses were stacked, with lenses 1 and 2 placed flush against one another (see fig. 9), while the offset for lens 3 was ~ ¼ mm. Alignment between the first two sets of lenses was guaranteed through the snapping together of specific features cut into the lens arrays. The alignment of lens 3 was purely visual and thus not as precise.

Collimated light was passed through the three lenses mounted on a positioning stage. The light spot produced immediately after lens 3 was measured to be 0.5 mm in diameter, corresponding to a concentration of 43.5X, approaching our goal of 49X.

Because the translation device for moving lenses 1 and 2 relative to lens 3 in order to compensate for the incidence angle has not yet been built, the acceptance angle of the lenses was tested without lens 3. Mounting lens 1 and 2 on a positioning stage, and rotating it relative to the source of collimated light, the acceptance angle range with no loss of quality in transmission was found to be approximately ±9.8^0, matching our goal.

Summary: We have designed a solar collector that will be composed of 50-mm-diameter sub-arrays, each containing ~100 5-mm plastic micro-lenses. Each micro-lens illuminates a stack of about four 0.7mm PV cells that collect sunlight from 400nm to 1600 nm with a theoretical efficiency approaching 50%. Each sub-array has internal solar tracking and alignment over a ±10° field, so a large array of sub-arrays only needs to coarsely track the sun. The refractive lenses in the design are thin so the optical transmission can be >90% and the optics will weigh very little. There are other optical properties incorporated in this design that help the photovoltaic cells to operate very efficiently. We are building a pre-prototype system now, and will describe our progress at the conference.

Future directions: For our first design, we chose a modest magnification giving 49 suns, and a tracking range of $\pm 10^0$. We are now designing similar lens systems with larger magnifications and greater tracking ranges. We will examine the cost tradeoffs associated with these variations. We are also studying the use of larger lenses—i.e. 7.5mm rather than 5mm. This will reduce the number of PV cells and the amount of on-board wiring.

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